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A 35 year High-Resolution Wave Atlas for Nearshore Energy Production and Economics at the Aegean Sea

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Abstract

The study enhances the coastal resource knowledge and discusses opportunities for wave energy in the Aegean Sea. A fine-resolution numerical wave model is utilised to provide results for the Greek coastal regions. The model ran for 35 years (1980-2014) estimating wave characteristics, and quantifying the wave energy potential in coastal areas. The results deliver the energy potential, variability, and site characterisation for the Aegean Sea.

The dataset is coupled with wave energy converters power matrices to provide for the first time a long-term analysis of expected power production. Performance of devices is highly dependent on matching the power matrix to the local resource, suitable devices can obtain capacity factor up to 20% and favour operation for low wave heights and high frequencies.

Based on energy analysis data, an economic performance and payback period of a hypothetical wave farm is examined. With little information on wave energy in the region, this preliminary cost-to-benefit analysis shows the viability of wave converters. Even with high capital expenditure associated with novel technologies, certain scenarios achieve amortisation periods at 7.5 years for a properly selected converter. Results are comparable with previous renewable schemes aimed at increasing the cumulative installation of other early stage technologies.

Keywords: Aegean Sea, Numerical Wave Model, Wave Climate, Wave Power, Energy Economics

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1. Introduction

The Mediterranean Sea is a semi-enclosed basin with small water boundaries, to the West at the Straits of Gibraltar, North-East a channel connects Northern Aegean with the Marmara Sea, finally at the South-East the Nile river connects the Egyptian Sea with the Suez Gulf and the Red Sea. External wave boundaries are not significant for the Mediterranean Sea, but the high distribution of islands around the Mediterranean increases the difficulties for wave estimates.

Study of the Mediterranean area has been indicated [1] for wave climate analysis and wave energy quantification. The past years studies have been conducted, with some drawbacks on temporal and/or spatial attributes. Spatio-temporal limitations are either focused on either very small areas [2] or encompass a limited duration period of analysis [3, 4, 5]. Such studies provided significant improvements in understanding of the regional wave climate, limitations in time duration, scale, and level of resolution are important to note.

To date most long term studies are associated with the Mediterranean Sea, amongst the first in 2004 a consortium of several institutions delivered 10 year Wind-Wave Atlas for the region, based however on a coarse oceanic model [6]. Ratsimandresy et.al [7] used the same coarse oceanic model to provide a 44 years ocean and atmospheric hindcast for the Western part of the Mediterranean. Recent studies by Mentaschi et.al. [8] and Ponce de Leon et.al. [9] presented Mediterranean wave power potential for 35 and 29 years respectively. The first study focused on Italy [8] and the second in the Balearic Sea [9], both of them using an oceanic model. Majority of studies are based on oceanic models with spatial resolution hindering extrapolation of results to coastal areas, as discussed in Canellas et.al. [10]. Usual spatial resolution utilised for numerical wave models in the region are between 0.1° ($\approx 11Km$) and 0.04° ($\approx 4.4Km$) [11, 12, 3, 13, 6, 8, 7, 14].

Concerning the Aegean Sea, most recent long-term and up-to-date wave climate analysis (42 years) is by Zacharioudaki et.al.[15], using the oceanic model WAM and assessed wave climate from 1960–2001, dynamically downscaled winds at 50 Km and a spatial resolution of 0.1° . The outcome assessed wave height variations and return periods, after an application of correction factors [15]. Emmanouil et.al. [16] used the same oceanic model forced by 3 hourly winds from the SKIRON model, and provided a 10 year hindcast on the wave content of the region (2001-2010). The study utilised spectral

discretisation of 25 frequencies and 24 direction, with a spatial resolution of 0.05° , and assessed several key statistical indices over the domain. Additionally, studies using unstructured meshes offered wave power resource estimates for the Aegean, using a 15 years hindcast [17, 18]. Prior to them a wind and wave Atlas 10 years in duration was presented by Soukissian et.al.[14] utilising an oceanic model. A summary of studies focused in the Aegean region are presented in Table 1, with information on models used, durations, and outcomes.

Table 1: Implementation of Aegean Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Aegean	[14]	WAM	10	$0.1^\circ \times 0.1^\circ$	Waves
Aegean	[19]	WAM	1	$0.06^\circ \times 0.06^\circ$	Waves
Aegean	[17]	MIKE21	15	Unstructured	Wave Power
Aegean	[20]	SWAN	1	$0.1^\circ \times 0.1^\circ$ & $0.025^\circ \times 0.025^\circ$	Waves, Wave Power
Aegean	[15]	WAM	42	$0.1^\circ \times 0.1^\circ$	Waves, Extremes
Aegean	[18]	MIKE21	15	Unstructured	Wave Power
Aegean	[16]	WAM	10	$0.05^\circ \times 0.05^\circ$	Waves, Wave Power

For the Aegean majority of studies use oceanic models with coarser resolution, this study aims to contribute and fill in the gap of fine-resolution information on the wave power resource for the Aegean Sea. The finer resolution with tuning of nearshore components, delivers detailed long-term energy estimates and allow to assess the opportunities for wave energy converters.

The temporal length of the datasets allows us to establish a comprehensive database of wave energy and device performance in the Aegean Sea. This is of major importance to decide on energy performance indices and outline the potential benefits for the Greek energy system. Results go further than just a wave climate analysis and contribute to energy assessment of wave converters in the milder waters of the Aegean Sea. The results are quantified per region and technology, allowing estimations concerning wave energy converters and deliver an up-to-date resource and techno-economic assessment.

The study is separated in the following sections, Section 2 presents the datasets, numerical wave model calibration, buoy validation, and comparison with recent studies. Section 3 quantifies and examines the wave resource in the coastal Aegean Sea and site classification. Section 4 presents the energy results obtained and classifies the utilised wave energy converters, according to their performance in the Aegean Sea. Section 4.2 provides preliminary information, concerning payback periods of potential wave energy applica-

66 tions, considering current and past schemes of renewable energy frameworks
 67 in Greece. Finally, Section 5 presents a summary of results and discusses
 68 future work.

69 2. Material and Methods

70 2.1. Model set up and Areas of Investigation

71 Simulating WAVes nearshore (SWAN) is a third generation spectral phased-
 72 average model used for wave studies [21]. The wind input is provided by
 73 NCEP and the Re-Analysis package of the CFSR dataset with 1-hour time
 74 intervals [22]. The model used a two way nesting for the Mediterranean and
 75 Aegean Seas, with a duration of 35 years from 1980–2014 for all domains, see
 76 Fig. 1. Buoy and additional selected locations for the Aegean Sea are given
 77 in Fig. 2.

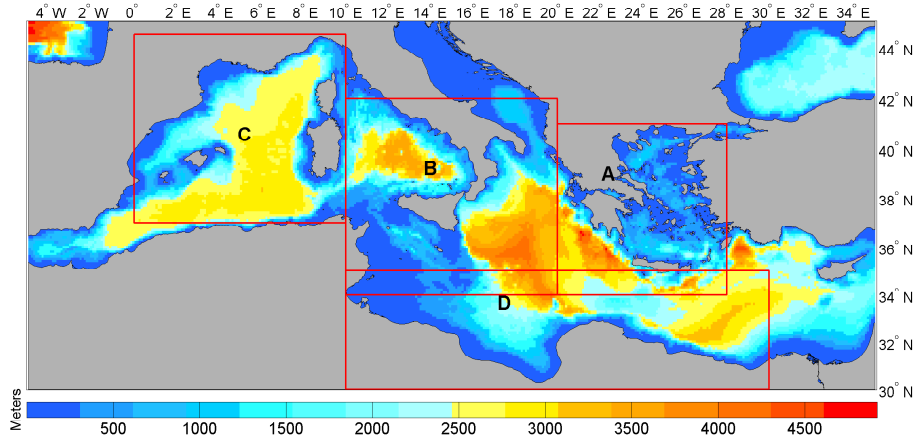


Figure 1: Initial domain utilised and subsequent nestings, A: Aegean Sea B: Tyrrhenian Sea, West Ionian, C: Balearic Sea, D: Libyan Sea (colorbar depth in meters)

78 The Mediterranean mesh was used to provide boundaries, the coarse res-
 79 olution of the domain is 0.1° . The Aegean was a nested domain and has a
 80 spatial resolution of 0.025° . The resolution in combination with all nearshore
 81 source terms activated allows for a better representation of coastal waters, in-
 82 creasing the confidence of results in comparison with oceanic models [23, 24].

83 Direction has been subdivided into 25 intervals and the frequency is dis-
 84 cretised in 30 bins, highest wave frequency is set to 28 seconds, the lowest

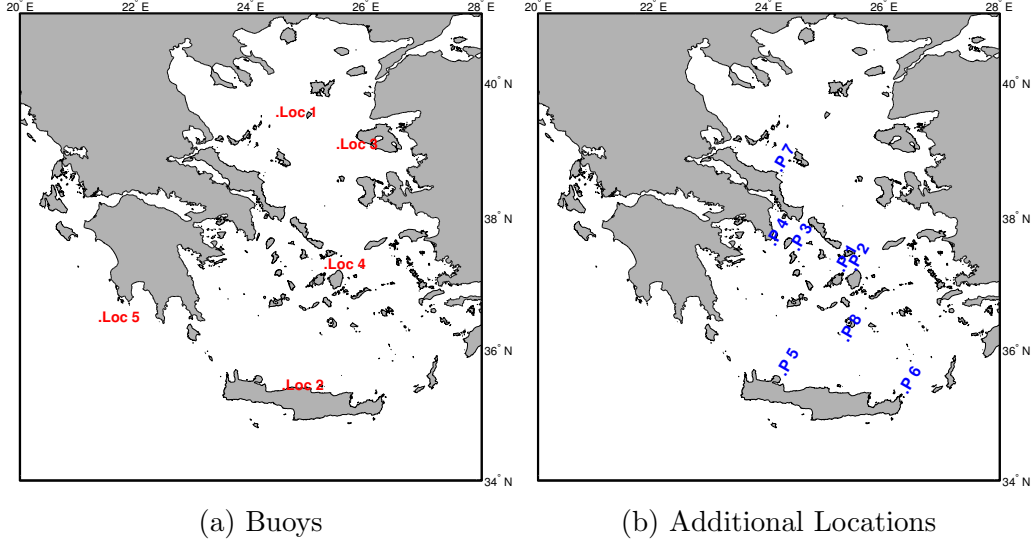


Figure 2: Buoys: Loc 1-5, Athos, Elmea, Lesvos, Mykonos, Pylos (panel a). Locations: P 1-8, Paros, Naxos, Kythnos, Attika, Crete1, Crete2, Euboeia, Santorini (panel b)

85 is 2 seconds and are distributed logarithmically ($\Delta f = 0.1f$). Selection and
86 range of frequency and directional bins, have a direct effect on computational
87 resources, with an increase in the parameters (frequency and directional bins)
88 not always delivering improved performance [25]. The coordinates are Spher-
89 ical and have been extracted from ETOPO-1 [26] and bathymetry domains
90 were constructed, using bi-linear interpolation.

91 The wind scheme is based on formulations by Komen [27] with a linear
92 growth coefficient activated [28]. Bottom friction, depth breaking, refraction,
93 diffraction processes all are used to account for wave interactions. Triads
94 are solved with the Elderky method [28], and quadruplets are activated in
95 a semi-implicit way. Due to the orography and sudden depth changes of
96 Mediterranean region, a backwards step and time propagation scheme is
97 used to ensure stability. Finally, all hindcast years were initiated with a
98 "warm" start configuration, i.e. hindcast computations start prior to the
99 year of investigation to avoid warm up errors in the model.

100 2.2. Calibration/Validation of Model

101 In the Mediterranean Sea, level of available buoy measurements infor-
102 mation varies. Italy's and Spain's buoy networks are one of the most de-
103 tailed with buoy measurements going back 20 years. For the Aegean Sea we

104 have considered the buoys provided by Hellenic Centre for Marine Research
105 (HCMR) [29]. The POSEIDON network buoys by HCMR [29] are publicly
106 available, while Spanish and some Italian buoys are not publicly available.

107 Discussion on problems in buoy operation and other recording methods
108 can be found in Cavaleri et.al. [30]. Availability of satellite data is known to
109 the authors, due to temporal restriction as indicated by other studies we have
110 not considered them. The fact that recordings have large gaps between pass-
111 ing of the satellites, 10 or 30 days apart, prompted to the decision. Another
112 limitation is their spatial coverage, satellite do not offer wave recordings at
113 the nearshore, but provide data further away usually at approximately $20Km$
114 off coastlines [27, 30, 31, 32, 33]. Even with the inherit problems of buoys
115 and measurement gaps, their positioning especially at nearshore waters offer
116 reliable considerations nearshore assessments.

117 The buoy data underwent a filtering process to exclude missing intervals
118 and outliers. The validation process was repeated for all available years,
119 Table 2 sums the validation of the model with buoy data. The indices used
120 have been presented in a previous investigation by the authors for the region
121 [20, 34]. The use of various statistical indices assist in the interpretation of
122 results, allowing better confidence in the models [35, 36].

123 Prior to Aegean domain validation, calibration based on wind scheme was
124 performed. Two wind schemes are considered, first scheme was presented in
125 Komen et.al. [27] and denoted WAM3, while the second was adapted by the
126 theory provided by Janssen and [37, 38, 39] denoted as WAM4.

127 Both solutions are options of the wind input source term of SWAN, and
128 dictate the evolution and wind interactions with waves. Difference of wind
129 schemes lay to some extent on wind coefficients, and especially the drag
130 coefficient at $10m$ height. Both formulations are based on Miles [40], although
131 basic difference are with the determination of wind drag coefficient and its
132 effects on fetch limited seas. More information on the difference of used
133 schemes can be found [41, 42, 39]. The selection of appropriate scheme has
134 to depend on the wind product used, since they provide the different temporal
135 and spatial information [43, 44, 22, 45], some alterations in the behaviour of
136 waves are expected. Increasing the temporal resolution of the wind input
137 has been reported to affect numerical wave performance by reducing under-
138 estimations [46].

139 WAM3 was activated with whitecapping coefficient (2.36^{-5}) and linear
140 wind growth. The WAM4 adaptation also had activated a linear growth,
141 and whitecapping coefficient set to 4.5.

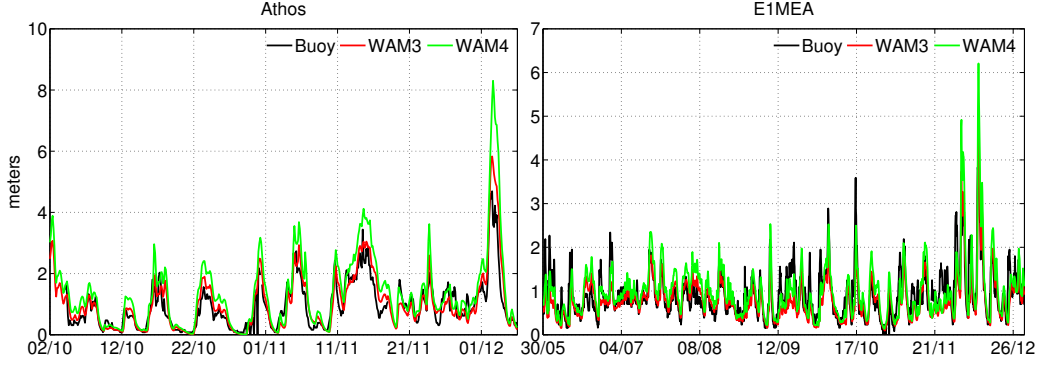


Figure 3: Hindcast under the wind schemes, with available 2013 H_{sig} buoy measurements

As seen in Fig. 3, both solutions offer good generation trends, with the WAM4 driven model recording higher peaks. More specifically for location E1MEA the comparison of available data and buoy measurements yields a correlation coefficient for H_s of 0.88 for WAM3 and 0.86 for WAM4. The bias in this case is much closer for the WAM4 scheme nearly zero ($0.014m$), while WAM3 under-estimates by $-0.17m$. The root-mean-square errors (rmse) are significantly lower for WAM3 ($0.4m$) while WAM4 acquires a value of $0.48m$. At Athos location, both models provide good correlation coefficient of 0.95, both over-estimating the results. In case of WAM3 the over-estimation is $0.1m$, while for WAM4 the over-estimation is $0.45m$. The rmse is much lower for WAM3 with $0.4m$ while WAM4 has $0.76m$.

Performance of models for wave periods, peak period (T_{peak}) has a correlation coefficient of 0.80 (WAM3) and 0.78 (WAM4) for the E1MEA locations. Both models over-estimated the period by ≈ 1 sec, scattering is less for (WAM4) 0.34 and 0.36(WAM3). For the Athos location, correlation coefficient are similar, 0.80 (WAM3) and 0.82 (WAM4). Both model over-estimate slightly with WAM3 (0.27 sec) and WAM4 (0.4 sec), the scatter index is 0.32 (WAM3) and 0.31 (WAM4).

From the comparison, WAM3 was considered as a physical solution, since it offered a high correlation and more representative wave heights in terms of magnitude, see Fig. 3; over-estimations can be attributed to the temporal resolution of re-analysis dataset .

After wind scheme selection, the coarse model run for 35 years to provide spectral (2-D) boundary information to the nested domain with a temporal

Table 2: Overall Validation indices for buoys considered in the nested mesh (H_{sig} in meters, T in seconds)

	Athos(2000-2014)			Lesvos(2000-2012)			Mykonos(2002-2012)			Pylos(2007-2014)		
	H_s	T_{peak}	T_{m02}	H_s	T_{peak}	T_{m02}	H_s	T_{peak}	T_{m02}	H_s	T_{peak}	T_{m02}
R	0.95	0.87	0.92	0.93	0.86	0.92	0.87	0.67	0.77	0.93	0.91	0.93
rmse	0.34	1.11	0.74	0.39	1.05	0.64	0.52	1.68	0.87	0.38	1.06	0.73
MPI	0.98	0.90	0.92	0.98	0.90	0.93	0.98	0.89	0.92	0.97	0.85	0.89
Average buoy	0.81	4.56	3.66	0.76	4.57	3.53	1.00	4.82	3.63	0.98	5.83	4.36
Average SWAN	0.82	4.45	3.24	0.89	4.45	3.25	0.87	4.70	3.26	0.99	5.59	3.96
Bias	0.01	-0.11	-0.42	0.13	-0.12	-0.28	-0.13	-0.12	-0.37	0.01	-0.24	-0.40
SI	0.41	0.24	0.20	0.52	0.23	0.18	0.52	0.35	0.24	0.39	0.18	0.17

step of 6 hours. Results from one year are presented in Fig 4. Table 2 provides the statistical validation of buoys with the longest recordings.

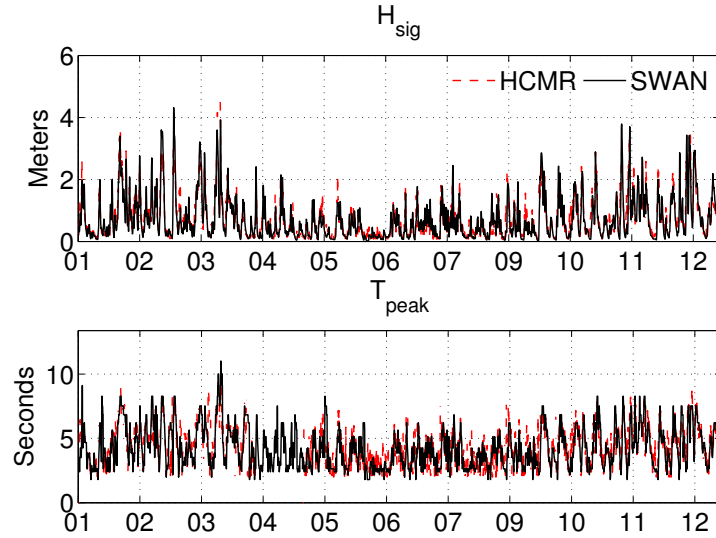


Figure 4: Validation of one of the datasets, for the year 2007 (12 months) Athos location (buoy HCMR)

Results are comparable with the latest study published by Zacharioudaki et.al. [15], reporting similar values even by utilising a different wind dataset and model. Scattering in our and the aforementioned study, present similar correlation coefficients, biases and rmse values are similar for all locations with some improvements in the Athos comparisons by our model. Lesvos presents over-estimations on H_s and at Mykonos small H_s under-estimations.

Our dataset also shows good agreement, with a nearshore model using a unstructured mesh by Jadidoleslam et.al. [18]. In same buoys locations we record improvements in all correlation coefficients for both H_s and T_{peak} . The aforementioned model offers less biases followed by consistent resource under-estimations. In terms of wave periods our modelled data show lower biases. The results provide confidence in our dataset and additional points are extracted based on the wave power spatial distribution, see Fig. 2.

3. Theory and Calculations

3.1. Wave Climate Variability Analysis

Due to the nature of waves, intermittent behaviour is expected, evaluation of seasonal and intra-annual changes provides with information concerning variations. Short hindcast of just few years are not able to assess and identify trends, at least 10 years of hindcast required for robust estimates are suggested [24, 47, 48]. Variability is for renewable energy projects. Without considerations on long-term fluctuations, confidence decreases for energy estimates [49].

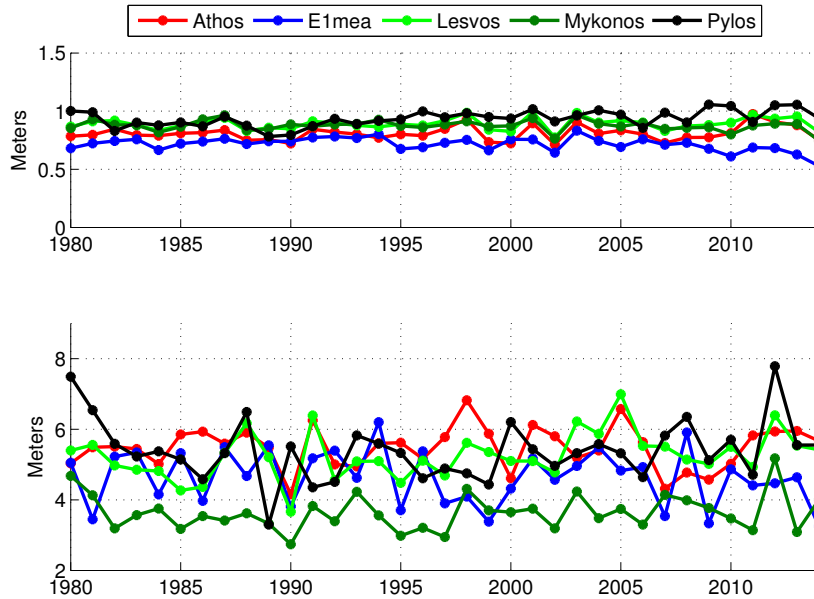


Figure 5: Annual mean (upper) and max (lower) H_s

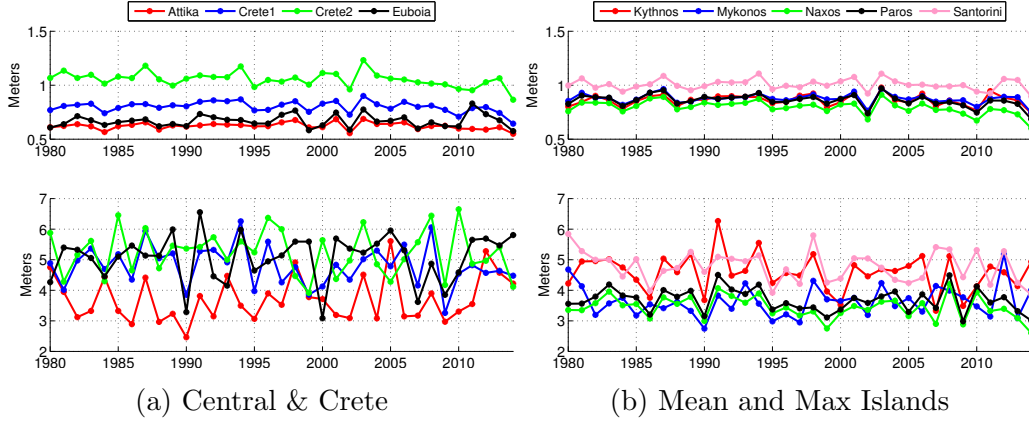


Figure 6: H_s mean (top row panels) and max (bottom row panels)

Throughout the hindcast, Athos and Pylos present high maximum values, with mean values almost consistent for Mykonos and Lesvos, see Fig 5. Slightly higher magnitudes are recorded at Pylos that is located at deep waters and exposed to swell components travelling from the West Mediterranean.

We have to note that maximum values show some variance, mean values of wave height do not deviate much until 1998. However, maximum events have significant differences, with Mykonos location having lower values, this can be attributed to its location in the Cycladic island complexes, where coastlines reduce incoming waves.

For the additional locations selected, annual behaviour is also examined. Because they are closer to coastlines, variation expected is less than deeper locations. Fig. 6 displays the regions at Cycladic islands and near Central Greece, results have similar magnitudes of resource and trends in annual means. Locations at Cyclades, Naxos and Paros, show similar values and trends. In both cases maxima values are significant reaching $\approx 6.5m$ at Crete 1-2, while locations closer to island complexes have consistent values of over $\approx 4.5m$, with the exception of Kythnos.

Similar to measurements, the magnitude of 95th and 75th percentiles exhibit higher values at South Aegean, West of Crete. The Central belt of the Aegean (Cyclades-Central Greece) and near the mainland coastlines has low values for both percentiles, while the island complexes attain higher values. Percentiles for the Northern coasts of the Aegean have smaller wave heights as expected. Deep water locations above the central region see higher the

214 values, with the resource significantly diminished as it propagates towards
 215 the Macedonian coastline.

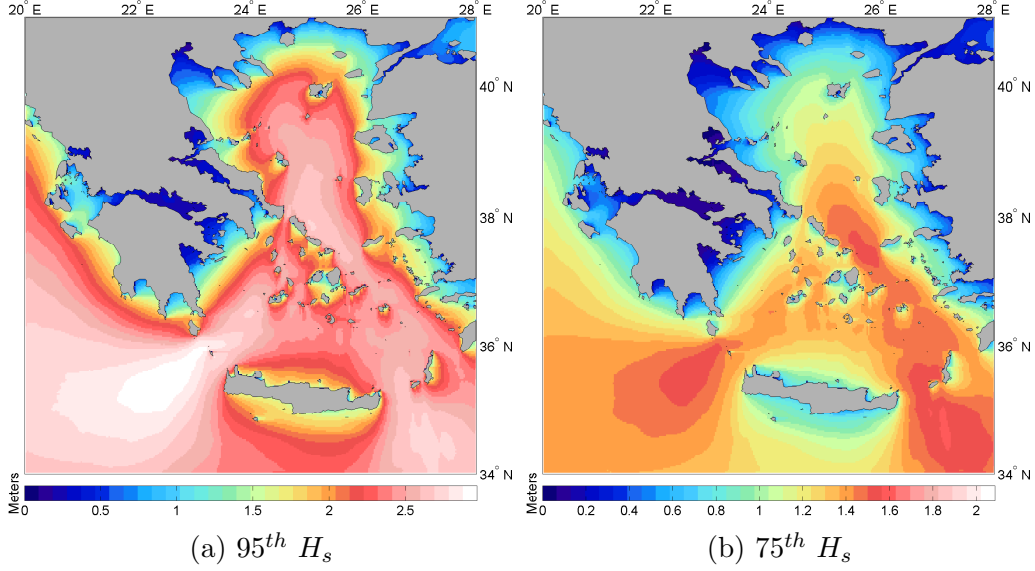


Figure 7: 95th panel (a) and 75th panel (b) percentiles in meters

216 The joint distribution (bivariate) gives the number of instances that wave
 217 height (H_s) and energy period (T_e) occur, providing with the dominant re-
 218 source characteristics. They can aid significantly in selection of appropriate
 219 wave converters. Current state-of-the-art wave energy converters are classi-
 220 fied according to their operational principles (see also Section 3.4) installed
 221 capacity and range of operation [50]. The joint distribution data allow for an
 222 initial dissemination and selection of potential appropriate device in terms
 223 of operation conditions. This can be considered as a feasibility investigation
 224 stage for converter selection.

225 The joint distributions utilise all 35 years of hindcast parameters to ex-
 226 amine the dominant seastates that occur at each location. The number of
 227 occurrences (recorded instances), are shown in each cell. The classification of
 228 every state corresponds to set interval of 1 sec (T_e) and 1 meter (H_s), while
 229 this can be reduced to 0.5 due to the amount of data within the dataset the
 230 previous classification was chosen for display purposes only.

231 For locations near central Greece dominant conditions in Attika are ex-
 232 pressed from 0.5-4 sec and H_s up to 1.5 meters. Euboia has a slightly higher
 233 minimum value from 1.5-4 sec and similar wave heights, see Fig. 8. Locations

234 at Crete (Crete 1 and 2), have a wider range of periods (2-7 sec) and frequent
 235 wave heights from 1.5-4 meters. The Cycladic locations (points Paros and
 236 Naxos), have higher occurrences at periods (3-6 sec) and wave heights from
 237 1.5-5 meters, see Fig.9.

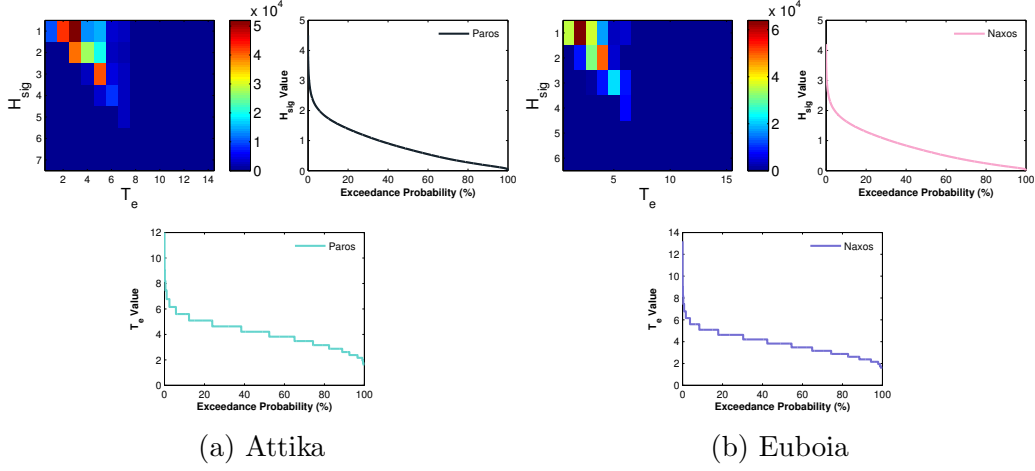


Figure 8: Number Occurrences and Exceedance (%), H_s in meters and T_e in seconds

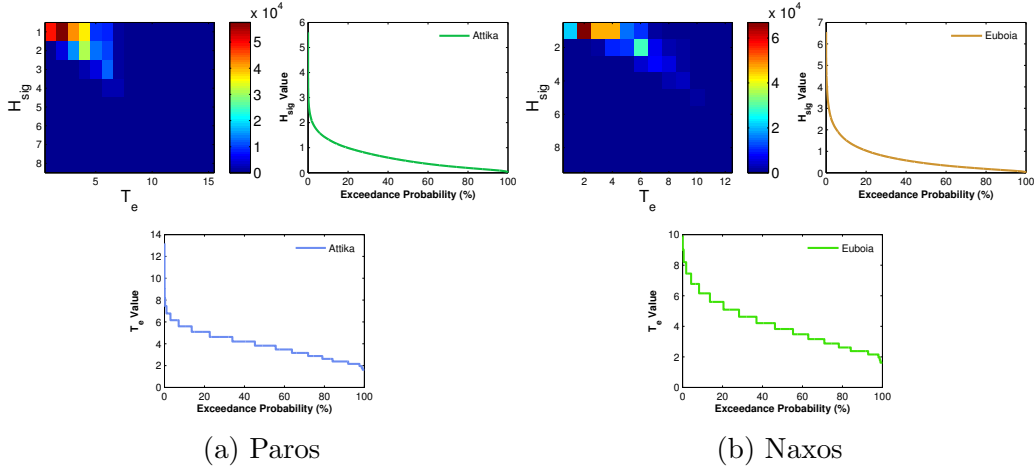


Figure 9: Number Occurrences and Exceedance (%), H_s in meters and T_e in seconds

238 Kythnos, Mykonos, and Santorini have similar maximum height (≈ 7
 239 meters), they also have similar joint distributions with periods of 2-6 secs
 240 and most commonly met H_s of 1.5-3.5 meters. Athos, Pylos and Lesvos

241 show H_s from 1.5-4 meters and a wider period range from 2-9 sec. The
 242 overall characterisation of the Aegean Sea, can be subsequently classified as
 243 favouring operational WECs that have a higher production yields at small
 244 wave heights and low periods (high frequencies).

245 3.2. Wave power resource

246 Estimated resource is based on the form of wave energy for irregular
 247 waves, with energy contained expressed in W/m , which corresponds to the
 248 energy per crest unit length. In SWAN energy components are computed
 249 with a formulation appropriate for the realist representation of resource, over
 250 the summation different wave numbers frequencies (f) and directions (θ).

$$P_x = \rho g \int \int C_{gx} E(f, \theta) df d\theta \quad (1)$$

$$P_y = \rho g \int \int C_{gy} E(f, \theta) df d\theta \quad (2)$$

251 where $E(f, \theta)$ the energy density spectrum over an x (longitude) y (lat-
 252 itude) system, C_g are the components of absolute group velocities, water
 253 density (ρ), g gravitational acceleration. Total wave power is estimated in
 254 W/m or kW/m :

$$P_{wave} = \sqrt{P_x^2 + P_y^2} \quad (3)$$

255 All locations are examined annually and per month, providing with mean
 256 wave power estimates assessing the fluctuation of encountered energy lev-
 257 els. Indicatively content locations are displayed in Figs. 10-11. The high-
 258 est levels of energy, as expected, are distributed over the winter months
 259 December-January-February showing similar trends for all locations. Dur-
 260 ing summer months most locations have a significant reduction wave energy
 261 levels, see Figs. 10-11. However this is not the case always for all loca-
 262 tions, from data which are not showed here the content of the Crete2, Naxos,
 263 Paros and Mykonos, seem to have a relative slight increase during July and
 264 August. The expected fluctuations of energy are less in "encapsulated"
 265 coastal areas in contrast to open seas, with propagated wave heights hav-
 266 ing "smoother"/lower magnitude due to reduction by bottom and coastline
 267 interactions.

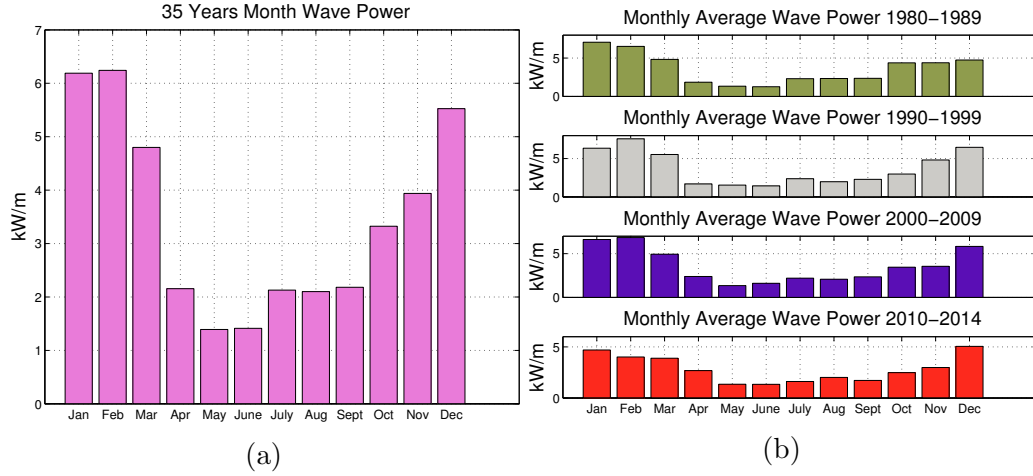


Figure 10: Crete 1 Wave Power, panel (a) overall monthly distribution, panel (b) monthly distribution per decade

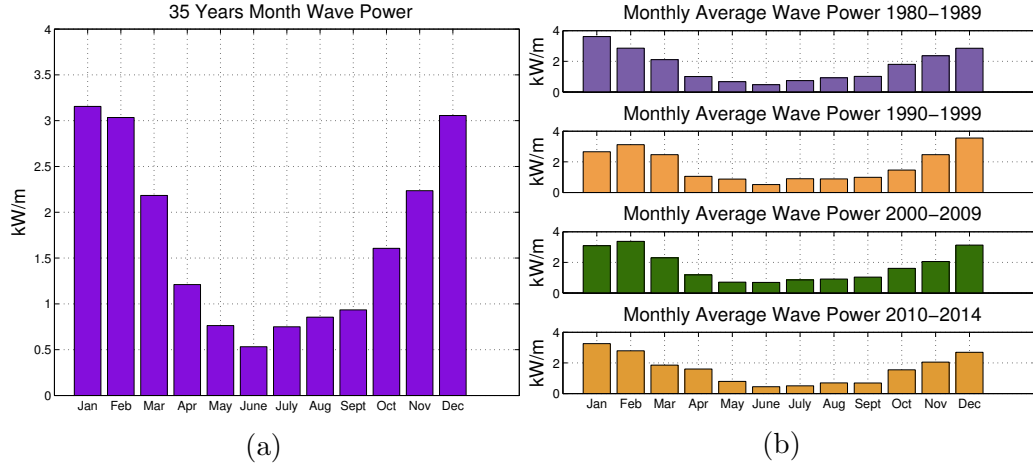


Figure 11: Attika Wave Power, panel (a) overall monthly distribution, panel (b) monthly distribution per decade

268 Annual maps of the Aegean present the wave energy (kW/m) for every
 269 year (i.e. 1980 from January 00:00 to 1st January 1981 00:00) and map the
 270 wave energy spatial distribution in the area. The seasonal separation of wave
 271 power resource has followed the established method: with winter December-
 272 January-February (DJF), Spring March-April-May (MAM), Summer June-
 273 July-August (JJA) and autumn September-October-November (SON), i.e.
 274 the seasonal resource of 1981 constitutes DJF: December 1980-January 1981-

275 February 1981 etc.

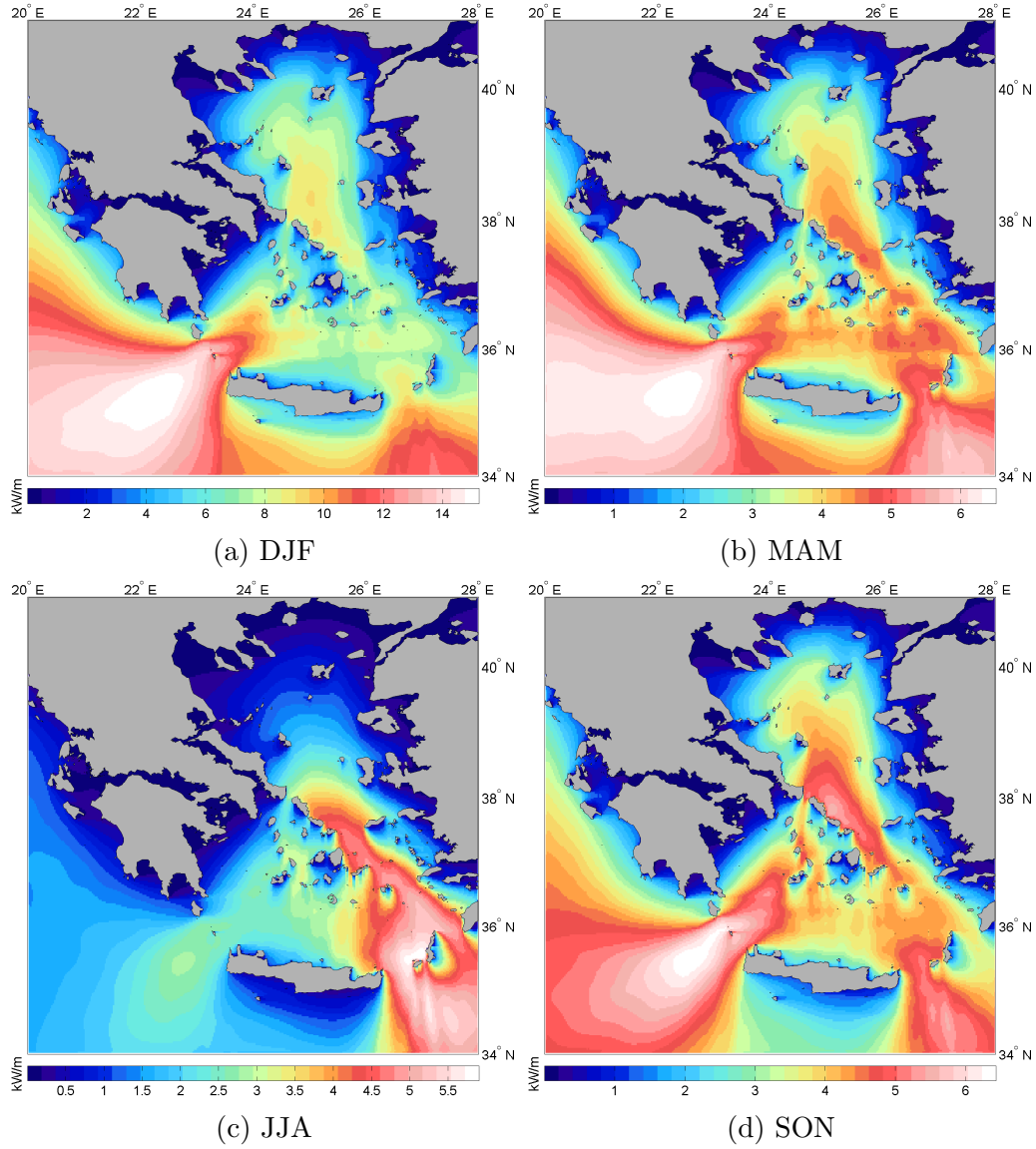


Figure 12: Seasonal Resource (kW/m) for the hindcast dataset

276 The seasonal resource assessment indicates that Southern parts of the
 277 Aegean are exposed to higher resources. Especially, waters around Crete
 278 and central island belt. Analysis of both maps and locations (annual and
 279 seasonal) indicate that highest resource are achieved through out DJF, SON

280 months with levels reaching up to 15-25 kW/m, while lowest months are JJA
 281 with values closer to 6-8 kW/m. Fig. 12 display the seasonal wave power
 282 levels from the hindcast, with DJF having the highest mean power flux.
 283 Similarly, high energy is attained in MAM and SON months, although most
 284 Cycladic areas have a higher resource levels throughout SON. Wave energy
 285 "builds up" from November till March, see also Figs. 10-11. In general terms
 286 the North Ionian, Central and South Aegean Seas acquire highest levels, with
 287 North Aegean having low values throughout.

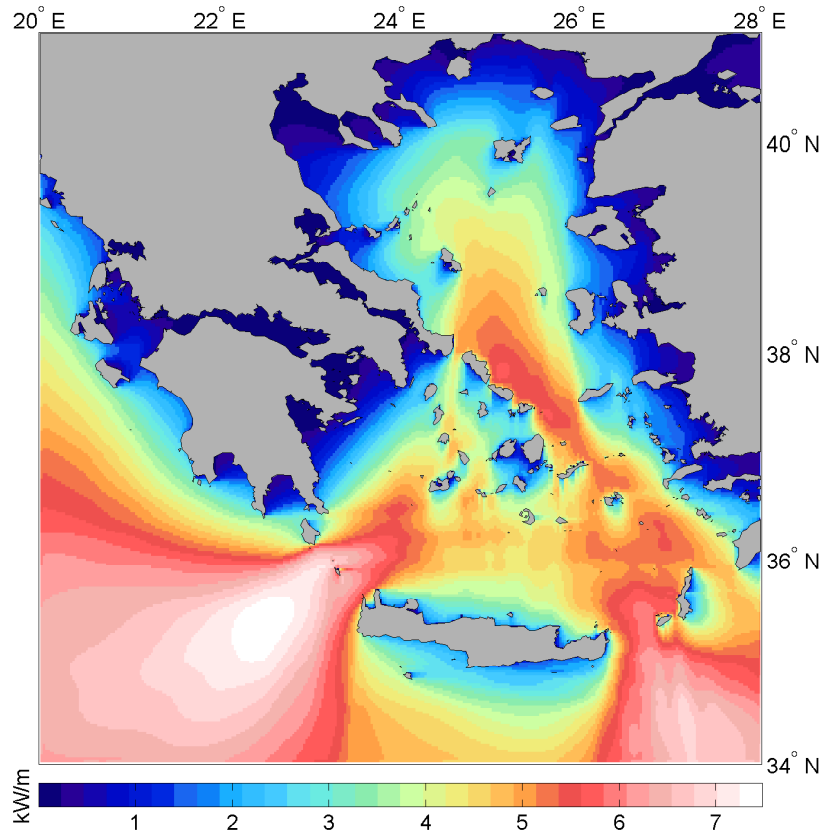


Figure 13: Wave Power (kW/m) 35 years dataset

288 The mean energy content of the region is presented in Fig. 13, with higher
 289 energy content is met at East and South of Crete with ≈ 8 kW/m. The
 290 Cyclades have 5 – 6.5 kW/m, although between the islands the resource is
 291 reduced. Northern coastlines have lower resource as also indicated by the
 292 seasonal analysis. North West part of the Ionian islands encounter similar

293 levels of wave power as the ones met in central regions.

294 With wave energy being a renewable resource, variability is a factor that
 295 affects production. Coefficient of variation (CoV) reveals most volatile areas
 296 of change, meaning that variation levels are higher in those regions leading to
 297 greater uncertainty. Coefficient of variation (CoV) (σ/μ) is associated with
 298 the mean (μ) and standard deviation (σ) of sampled data. If the CoV is 0,
 299 then the values do not present fluctuations, on the other hand if CoV is 1
 300 then strong variations exist and may affect performance [13]. Coefficient of
 301 variation over a long period of time, ensures the inter-annual fluctuations are
 302 incorporated into examination of the variability levels in the region.

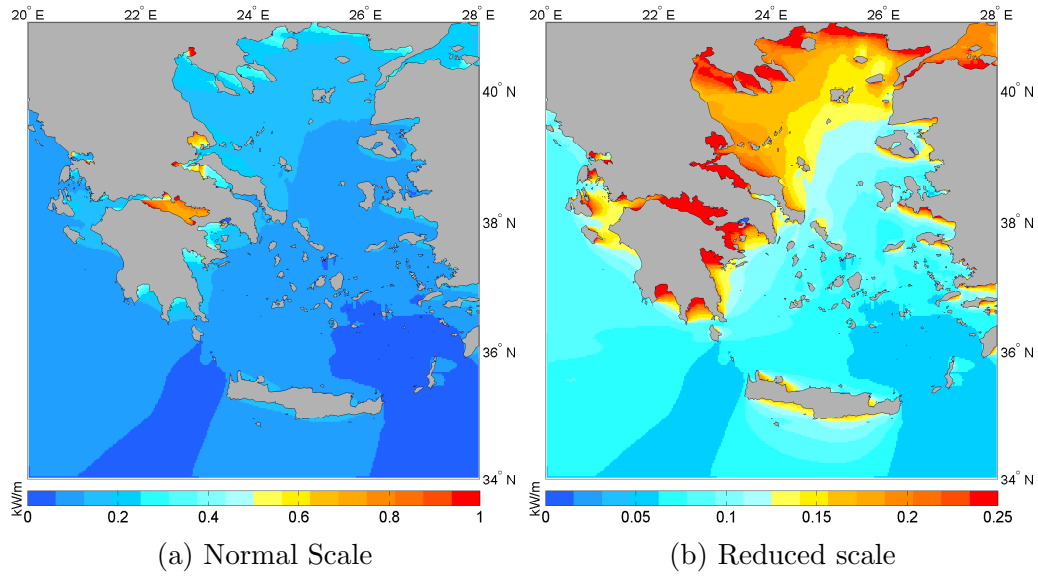


Figure 14: Wave Power (kW/m) coefficient of variation for the Aegean Sea with the 35 years dataset

303 Due to the interaction of propagated resource with bathymetric changes
 304 and major coastlines, CoV is higher at nearshore locations such as the Cy-
 305 cladic islands, see Fig. 14. Highest levels are located in the straits of Ko-
 306 rinthos between Peloponnesus and Central Greece, followed by the Pagasetic
 307 Gulf and Malian Gulf. The first location is exposed to locally wind gen-
 308 erated waves with, as the location closely resembles encapsulated area with
 309 low depths. As stated depths variations around Greece are quite sudden with
 310 the majority of having values close to shore around 60 meters, while sudden
 311 changes lead to extremely deep waters of more than 500 meters [26, 51] and

Fig. 1. These sharp changes add to the complexity of wave breaking due to bottom interactions, shoaling and diffraction. Similarly the North regions coastal of Macedonian (Thermaikos Gulf) and Thrace (Thrakiko Pelagos), while exposed to lowest resources their annual variations presents a high variance level.

Cycladic island many coastline profiles reducing wave heights which affects the resource levels. Crete presents levels slightly higher after the presence of small Peninsulas, for example at the Chania Peninsula. The South region of Attika is freely exposed to the Aegean Sea and has higher variation. Locations at the coast of Central Euboia have high deviations, partially due to resource dependence on coastal and bathymetry characteristics.

As expected, winter months are the most energetic with lowest resources given constantly throughout the years for summer months. The regions, especially at the Central Aegean, incorporates a difficult bathymetric environment but has an almost consistent energy flow, with small variations. These reductions are generally encountered to areas for which the coastal environment is involving complex shorelines and multiple obstacles (land masses), Southern part of the Cyclades which is exposed to larger fetches has a better resource and smaller variations.

3.3. Wave Energy Development Index (WEDI)

Mean ($\overline{P_{wave}}$) and maximum (J_{wave}) wave power are important for identification of promising locations. Use of multiple indices aids in the dissemination of the local resource. The coefficient of variation revealed the potential changes in the energy resource for the region. Expanding upon that, the Wave Energy Development Index (WEDI) considers the interactions and severity of the resource at locations. A low WEDI with a high mean resource index can prove beneficial for WECs, when considering resource interactions, accessibility, and availability for energy production.

$$WEDI = \frac{\overline{P_{wave}}}{J_{wave}} \quad (4)$$

The index is the ratio of annual average wave power to the maximum storm wave power that every offshore device or structure will absorb. Devices are usually placed based on mean power content distribution, however depending on both the mean and maximum power potential influences of waves at the location can measure and penalise areas with a high index as discussed in Hagerman [52].

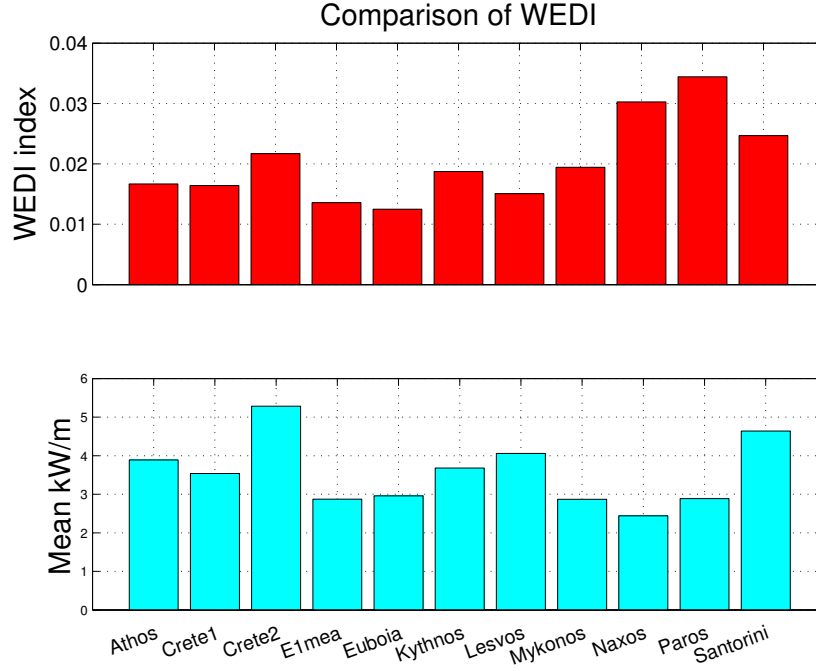


Figure 15: WEDI Locations for 35 years

346 WEDI takes into account the maximum extreme (storm) values of power
347 and assigns a corresponding level index that can be translated into potential
348 increase/decrease of maintenance and operation [53, 54]. The higher the
349 WEDI then locations will potentially require more capital expenditure for
350 infrastructure. Suggesting that potential sites should not only be consider for
351 their mean content, but also as a ratio of the maximum content. Covariance
352 and the interaction of the resource though WEDI can reduce the level of
353 uncertainties concerning the survivability of converters, minimizing CAPEX,
354 OPEX, and achieve consistent operation.

355 WEDI at the Cyclades islands is amongst highest ranked region of the
356 Aegean indicating, that the location resource is affected by storm events.
357 These findings have to be taken into account for structural and economic
358 considerations for development of wave farms.

359 Overall, from studies completed by the authors at various regions and
360 especially the energetic coastlines of Scotland and the United Kingdom [55],
361 the WEDI expressed in the Aegean region is far more consistent and less
362 variant. This comes in expense of energy production, but survivability and

operation of the devices is expected to obtain a more constant production rate.

3.4. Wave Energy Converters Application

Wave converters produce energy based on local characteristics of wave height and period. This joint distribution provides the representation of sea occurrences in an area. While many technologies exist, not all of them are appropriate for every wave environment. Studies suggest that application of WECs should always consider the wave climate of locations. In milder regions such as the Mediterranean countries suggestions for hydro-dynamically scaling devices down to match the local wave environment have been proposed [56, 57, 58, 59, 60].

Several devices are coupled with locations via power matrices as found in various studies [61, 50, 62]. These are used to indicatively assess the energy performance of multiple WECs for several coastal locations, as identified by the resource assessment. WECs selected for each location have been based on the depth characteristics of areas and proposed practices [24]. The WECs used in the study represent both deep and shallow water technologies, although no coastal applications are taken into account. More detail discussions on technical characteristics of WECs are discussed in several studies [50, 63, 58, 62, 64, 65].

Power matrices account for the production of the extractable energy by a WEC based on joint wave distribution. Though, other ways exist in order to calculate the energy levels, power matrices are the most commonly used. For a more detail analysis on the production in case of multiple devices and their wave-wave interaction [50, 66], discusses alternative computational fluid dynamic models (CFD).

As seen in Figs. 16-20 the characteristic periods (T) and H_{sig} are different for each converter. From a first glance we expect that the local environment will favour converters which tend to have a cut-in operation and maximum output at lower wave heights i.e. WaveStar, see Fig. 20. The devices are classified according to existing literature to shallow and deep (mid-depth less than $\leq 150m$). Obviously, not all of them are applicable at the locations, see Table 3.

We have examined the production levels at all coastal and nearshore

¹WaveStar based on its operation can be deployed at higher depths [50, 66, 67]

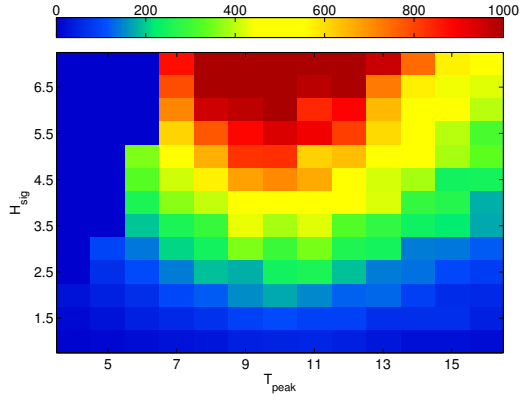


Figure 16: F-2HB power matrix (kW)

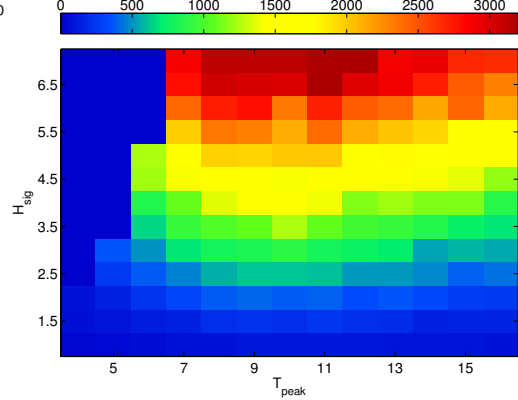


Figure 17: BOF power matrix (kW)

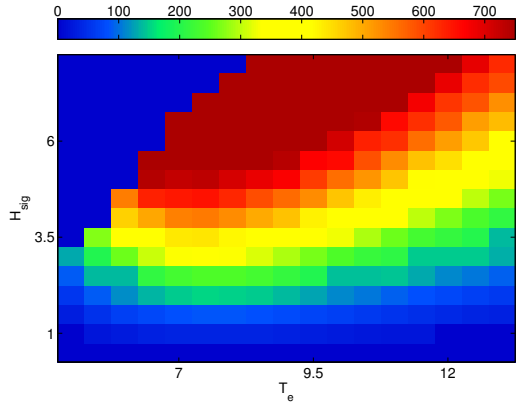


Figure 18: Pelamis power matrix (kW)

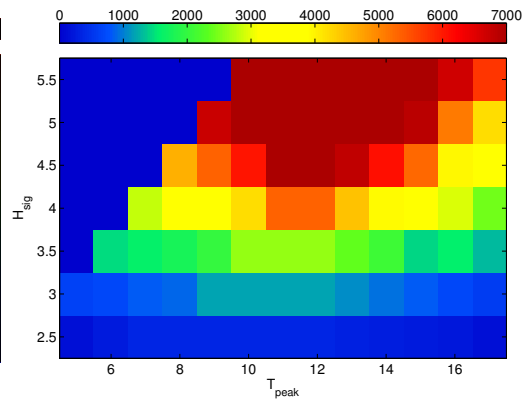


Figure 19: WaveDragon power matrix (kW)

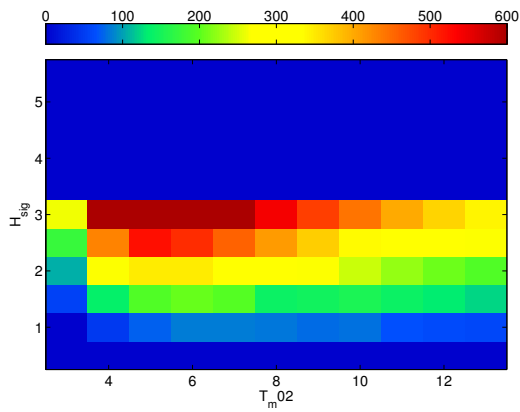


Figure 20: WaveStar power matrix (kW)

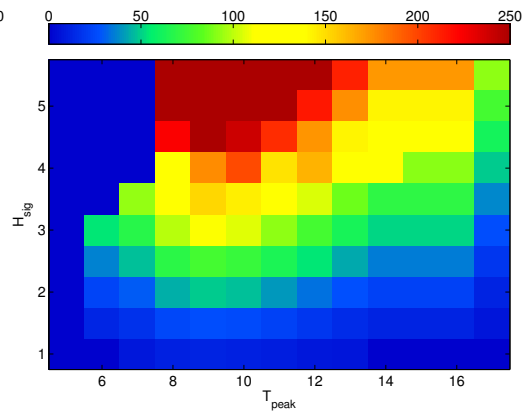


Figure 21: AquaBuoy power matrix (kW)

Table 3: Device classification according to depth

Wave Energy Converter (WEC)	Nearshore	Deep	Operational Depth (h)
Bottom Oscillating Flap (BOF)	X		$h \leq 50m$
WaveStar ¹	X		$h \leq 50m$
Floating two body heave converter (F2HB)	X		$h \leq 50m$
Pelamis		X	$h \geq 50m$
WaveDragon		X	$h \geq 50m$
AquaBuoy		X	$h \geq 50m$

locations, for over a period of 35 years. As installed capacity of each device, the maximum allowed power production was taken into account, similar to when examining other renewable technologies i.e. wind turbines.

The use of multiple devices in the selected locations reveals not only the compatibility of each device for the wave environments but also levels of expected production by bigger array of devices. Because the Aegean Sea is exposed to almost three times less the average energetic wave resource in comparison to the oceanic coastline, device selection has to account dominant conditions to maximise the energy production, selecting a WEC should not only rely upon installed capacity (kW) but also on characteristics of operation.

The power matrices utilized in this study have not been scaled down to match the specific areas, but provide a first glance on the feasibility and best applicable devices. Downscaling can be performed either through applying a Froude criterion and re-estimating the power matrices as seen in Luppa et.al. [68], or by utilising hydrodynamic models with specified input conditions appropriate to the local seas (as taken from the database) and constructing the scale power matrices as seen in Babarit et.al. [50] and Bozzi et.al. [58].

Estimating production with long-term data series allows for a robust estimation of capacity factors (CF) for all devices in the region. Based on available recordings, final estimations of production and CF by a device is not only based on annual data, but on the overall 35 years. Data used are extracted from the nested higher resolution domain and correspond to one hourly wave parameters, annual total time is ≈ 8760 hours (except for leap years) with overall datasets per location including $\approx 306,000$ hours. This implies that final proposed capacity factors per area are extensive, include intra-annual variations, and downtimes due to storms or very mild seas, though no consideration on the required maintenance hours is considered.

425 However, concerning downtime for maintenance is not expected to alter the
426 results significantly, since most of the times maintenance work is carried out
427 on very mild sea states, which are indirectly taken into account.

428 Estimation of capacity factors offers an improvement to the perception
429 of WEC performance in the areas, and exhibit that even without hydrody-
430 namical downscaling, devices are able to produce amounts of energy and can
431 easily compare to other mature and technically advanced technologies such as
432 photovoltaic and onshore wind. Some studies have suggested that by specif-
433 ically creating a more "generic" device adapted to the Mediterranean Sea
434 is expected to boost performance and capacity factors enhancing the energy
435 production and potential decrease of costs [58, 5, 69].

436 4. Results

437 4.1. Wave Energy at the Aegean Sea, the case of Greece

438 The electricity system in Greece can be classified in two distinct ways
439 as the central connected region (continental), and dispersed non-connected
440 electrical networks (islands). This arises the opportunity for wave energy
441 to be considered in combination with other renewable energies for the vast
442 number of de-centralized islands. The locations and spatial wave maps anal-
443 ysis (see Figs 12-13) represent a thorough and robust energy quantification
444 of the opportunities for wave energy applicability.

445 Extracted additional locations give focus on decentralized islands, and
446 examine the potential contribution by wave energy. The authors would like
447 to point out that although average annual and seasonal maps for wave energy,
448 wave height, and period are constructed, due to publication limitations, the
449 present analysis uses overall mean maps. With a variety of monthly, annual
450 and seasonal products developed and accompanying our database.

451 A long-term hindcast allows for characterization and estimation of po-
452 tential power production. Indicative locations have considered one device
453 installed. Although, the same results can be used to extend in nearby areas
454 for consideration of wave energy farms with multiple same devices.

455 Production is estimated in expected GWh per year, see Table 4, with ca-
456 pacity factors given per technology and location. Identifying the exploitable
457 energy content and quantify expected production by-off-the-self technologies.

458 On absolute energy production terms WaveDragon dominates the results
459 followed by BOF. Remainder WECs have similar levels of production, with
460 the lowest expressed by AquaBuoy. WaveDragon has rated capacity (7MW)

Table 4: Expected Production ($\approx GWh$)

	Crete 1	Crete 2	Kythnos	Paros	Naxos	Attika	Eubolia
BOF	1.61	2.24	2.19	2.77	2.43	1.66	1.23
WaveStar	0.74	1.05	0.92	1.10	1.10	0.85	0.56
FH2B	0.58	0.80	0.75	0.93	0.81	0.57	0.43
Pelamis	0.57	0.80	0.84	1.28	1.12	0.67	0.39
WaveDragon	8.06	11.43	11.51	8.33	6.09	7.34	5.92
Aquabuoy	0.17	0.24	0.22	0.23	0.17	0.16	0.12

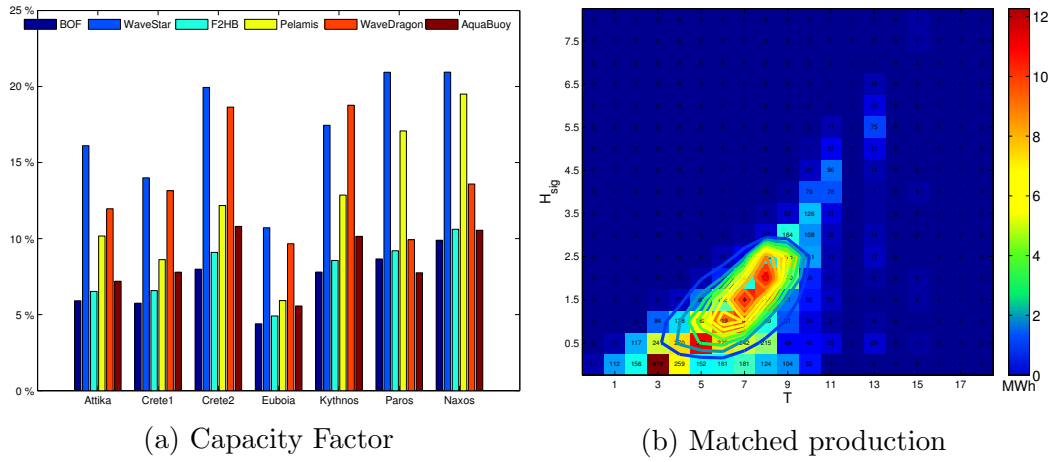


Figure 22: (a) Capacity factors by various WECs, (b) matched production with occurrences for Crete2 in 2000

461 and was expected that production levels would be significantly greater. This
462 though is not coming without a cost, since the higher the rated capacity then
463 capital expenditure is increased.

464 Even so, the goal is to obtain the best performance i.e. energy production
465 with lowest cost. Robust identification of capacity factors is a crucial compo-
466 nent for the determination of most suitable device for the region. Extensive
467 simulation analysis allows to estimate the annual expected energy extracted
468 by each device, and indicative numbers of capacity factors that can be of use
469 throughout the Greek region.

470 In Fig. 22 the corresponding capacity factors over the aggregated period,
471 for such resources the most useful operated device is the WaveStar, with sig-
472 nificant less rated power (600kW) than WaveDragon which provided highest
473 energy yield. Pelamis also attained consistent production throughout South-

Table 5: Capacity factor per Device and region

Device/Locations	Crete	Central Aegean	Central Greece
BOF	7%	9%	5%
WaveStar	17%	20%	13%
F2HB	8%	9%	6%
Pelamis	10%	16%	8%
WaveDragon	16%	14%	11%
Aquabuoy	9%	9%	6%

ern regions. F2HB, BOF and Aquabuoy present similar performances for all areas under 10%. In panel (b) of the same figure the annual number of occurrences are correlated with the production of WaveStar. The coloured contour represent the energy production of the WEC, while the background coloured box plot present the number of occurrences. The lowest operational characteristics of WaveStar match and favour enery production as this is expressed in higher capacity factors.

As mentioned, not all devices are suitable for all locations though we chose to effectively assess all devices and explore couple WEC production. Exact depths are not easy to calculate, due to spatial limitations when constructing the bathymetry profile, wave energy resources are expected to be similar at nearby coastal locations. The elaborated sharp changes of the Greek territory also suggest that distances from shore will be very small, even for depths of 150 m underlining careful consideration of area selection.

As the study focused on several locations, we can consider capacity factors per device and region as follows in Table 5. The area with highest potential levels of utilisation is the Southern and Central Aegean. With suitable to resource WECs presenting CF over $\approx 10 - 20\%$.

From generation information, capacity factors, distribution, and resource levels it is obvious that low wave height and high frequency devices operate much better, due to the low resource expressed in the areas. Components which comprise wave energy resource in the Aegean, indicate that WECs with lower operational ranges are highly favoured. This is directly correlated to the availability of resource, devices which achieve higher CF have nominal power at lower H_s and high frequencies (short second periods), see Figs. 16-21.

Specifically, Wavestar is more suitable because it achieves peak production at lower wave heights ($\leq 3m$) and shorter periods (high frequencies),

502 matching dominant lower resource conditions better. We have to underline
503 the fact that energy quantification is based on publicly available power ma-
504 trices, which entail levels of uncertainty in production from $\pm 20 - 40\%$ [50].

505 Another issue potential affecting WECs is effect of directionality, although
506 such information concerning the power matrices are not available publicly.
507 Swell direction is not involved in our computing power analysis, it is impor-
508 tant to emphasize that it can be a parameter to consider when installing
509 a power converter at a specific site, since many of them use the most fre-
510 quent direction as a design parameter, like the Pelamis. A future custom
511 site selected analysis is required to determine the "shadow" effects and dif-
512 fusion of energy by wave farms. Such analysis can be achieved by coupling
513 focused hydrodynamic modelling, and wave farm interactions analysis. This
514 can also lead to the determination of a hydrodynamically downscaled con-
515 verters suitable for the resource, reducing capital expenditure and increasing
516 performance.

517 *4.2. Preliminary Economic Evaluation with Regional Adaptation*

518 Currently in Greece all renewable installations are provided with a Feed-
519 In-Tariff (FIT) from the Greek government based on region and contribution
520 to system (centralized or decentralized). Higher FITs are provided to island
521 regions in order to maximize the use of RE and reduce energy dependency by
522 fossil fuels. So far the consideration of the Greek State have been solely based
523 on the development of wind, photovoltaic, solar and some level of biomass, no
524 consideration or appropriate pricing exists for the development of innovative
525 technologies in the region such as wave energy [70].

526 In addition, current investment schemes provide some level of subsidiza-
527 tion activities including energy production; latest developments have ex-
528 cluded photovoltaics and wind. The authors believe the proposed installation
529 of WECs can be classified as an investment of highly technical and skilled
530 nature allowing it to be included in the umbrella of the legislation [71].

531 The above legislative framework separates the region of Greece into sub-
532 divisions allowing higher levels of potential subsidies in the island regions
533 of the Aegean, where as shown in the previous sections the wave energy
534 potential is greater [71]. These subsidies may vary from 30% – 50%, with
535 current FITs subdivided according to technology, selling prices of electricity
536 by offshore wind is 105Euro/MWh, and island based photovoltaic 260 – 290
537 Euro/MWh regardless of installation capacity. RE produced electricity is

538 sold at priority to the Greek electrical operator. This ensures that the in-
539 vestment of green technologies is allowed priority grid penetration, while
540 selling electricity price is guaranteed for 20 years of contract (10+10 years).
541 Considering the innovative nature of the technology and the fact that it is lo-
542 cated offshore, the authors considered a range of proposed prices spanning
543 from 150-250 Euro/MWh, as is the case for de-centralized connected photo-
544 voltaics [70].

545 Apart from energy generation estimation, the investigation of adapted
546 cost is imperative for the areas, providing with preliminary results of asso-
547 ciated costs and levels of amortization periods. Costs for wave energy are
548 mostly associated with Northern European countries for which wave energy
549 has been looked at to a much higher degree. Here associated CAPEX and
550 OPEX are based on a scaled down approach of cost, taking into account the
551 milder seas and conditions that are encountered. Infrastructure and initial
552 work cost associate relevant areas and their extreme values by assigning a
553 proper percentage for maintenance and operation taking into account local
554 environment and infrastructure.

555 Studies that have examined the cost of wave energy converters, though
556 at initial stages suggest that WEC cost should always be considered based
557 on the device chosen [72, 63, 73, 74, 75, 76]. Studies suggest cost of the
558 power-take-off (PTO) of a device ranging from 2,000,000 up to 3,500,000
559 Euros/MW. This corresponds to devices using material and structural consid-
560 erations based on far higher energetic Seas (i.e. Atlantic exposed coastlines),
561 the authors consider them as CAPEX ex-works cost. It is logical to expect
562 that adaptation of a device in the milder Aegean environment will require
563 less CAPEX, thus one can consider (depending on technology) that the cost
564 will start at 1,750,000 to 2,000,000 Euros/MW, with less need for mooring
565 strengthening and other infrastructure cost reduced in comparison with the
566 reported for the European Atlantic costs.

567 The lifetime of a wave farm taken as 20 years, while indicative consid-
568 eration on operational costs and infrastructure (works costs) examined and
569 presented. However, some assumptions are made in terms of the economic in-
570 dices, the energy estimations are improved in comparison to previous studies
571 with capacity factors based on a thorough energy assessment.

572 The authors have considered that the CAPEX cost has the highest influ-
573 ence. In Table 6 all financial considerations of the scenarios are given, with
574 CAPEX representing the ex-works costs, installation ($inst_{cost}$) and mainte-
575 nance costs (m_{cost}) being a specific percentage of CAPEX. Selling price of

576 electricity considers inflation (g), rate of return (i), energy escalation (e),
 577 potential subsidy (γ), and capacity factor (CF) are assigned constant values.
 578 The CAPEX has been assigned in a range of 1.5-3.5 million Euros/MW, and
 579 is incrementally increased by 500,000 Euro.

Table 6: Financial considerations on the cost of a wave energy farm

	CAPEX	$inst_{cost}$	m_{cost}	c_o	g	i	e	γ	CF	P_o
Scenario 1	1.5 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 2	2 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 3	2.5 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 4	3 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 5	3.5 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10

580 Additional revenues are expected for RE by introduction of CO_2 permits
 581 sold through the Emission Trading Scheme (ETS), for the avoided cost of
 582 carbon used in electricity production. While this can be a significant added
 583 revenue stream, it has not been taken into account. WEC downscaling using
 584 hydrodynamic modelling for the region is expected to reduce overall CAPEX,
 585 and shortening the payback period significantly. The energy calculated and
 586 annual revenue stream for financial estimations are based on the proposed
 587 method by Kaldellis [77]. With initial capital (CAPEX) including the I_{Cn} ,
 588 works cost ($inst_{cost}$) and installed capacity for every MW installed (P_o).

$$I_{C_o} = [(I_{C_n} \cdot inst_{cost}) + I_{C_n}] \cdot P_o \quad (5)$$

589 The fixed annual cost for $M\&O$ (m_{cost}) calculated by the assigned per-
 590 centage of maintenance, and values are estimated for current money prices,
 591 over years (n). The annual fixed cost (FC_n) expenditure allows to calculate
 592 the cost to benefit (C_n) of the wave farm.

$$FC_n = m_{cost} \cdot I_{C_o} \cdot \left[\frac{1+g}{1+i} + \dots + \left(\frac{1+g}{1+i} \right)^n \right] \quad (6)$$

$$C_n = I_{C_o} + FC_n \quad (7)$$

593 Annual revenues are estimated by adapting the CF with installed capacity
 594 over one year period providing the annual energy (E_o), with the finalized
 595 earnings of each year adapted to current prices.

$$R_n = E_o \cdot c_o \cdot \left[\frac{1+e}{1+i} + \dots + \left(\frac{1+e}{1+i} \right)^n \right] \quad (8)$$

596 The final amortization periods, i.e. "break-even" scenarios, are estimated
597 by accumulated gains of each years adjusted to current prices R_n , and the
598 C_n of the wave farm.

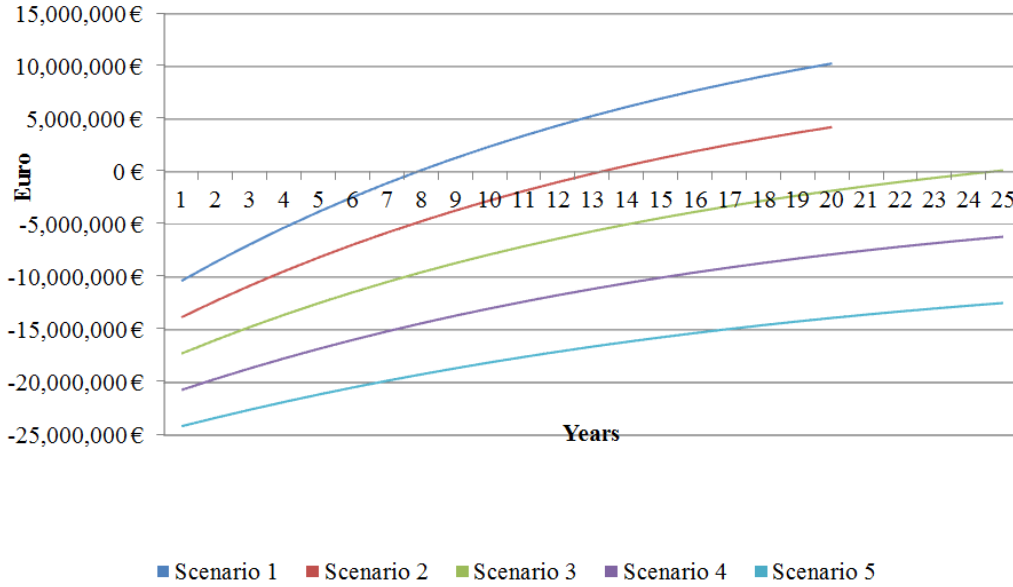


Figure 23: Payback Period for Scenarios, with y-axis monetary terms and x-axis the years of operation

599 The preliminary considerations on wave energy amortization periods show
600 the potential payback for such an investment concerning different scenarios,
601 see Fig. 23. Based on the assumptions Scenario 1 offers amortization within
602 7-8 years, Scenario 2 requires 12-13 years, Scenario 3 requires $\approx 22.5^1$, while
603 Scenarios 4-5 never break even.

604 Of course as explained there is not a specific legislative framework sup-
605 porting wave energy in the region, thus assumptions taken into account espe-
606 cially the electricity selling price and investment subsidization are expected
607 to affect the results. Based on previous experience with other technologies
608 applied in the Greek Market through 2000 – 2008, first stage PV park in-
609 stallations were given 50% subsidies while the FIT (for a then immature
610 technology) was 450 Euro/MWh.

¹Extended to 25 years to observe whether break-even is achieved

611 Another important factor is the economic uncertainty, especially of CAPEX,
612 associated with such pre-commercial technologies. Sensitivity of the payback
613 period depends highly on CAPEX, thus a further investigation on reducing
614 CAPEX by exact specifications of materials and costs used in a hydrody-
615 namically downscaled WEC may accelerate the technology.

616 Initial findings show that the adaptation of wave energy can lead to invest-
617 ment considerations even Technology Readiness Levels (TRL) of such new
618 technology, with additional improvements and clarifications in the regulatory
619 and legal frameworks required. Although, as shown in the analysis for wave
620 energy, variability of capacity factors and generating performance is heavily
621 dependent on the selection of the appropriate device to be implemented and
622 scaled to the location.

623 Thus, this extensive study has allowed a long-term estimation for the
624 indicative technologies and their utilization rates for Greece. The authors
625 would also like to repeat that energy estimations are based on published
626 power matrices; by obtaining more detailed information available by devel-
627 opers, we expect a better understanding of the opportunities.

628 5. Conclusions

629 In this study the wave environment of the Mediterranean and Aegean
630 region was hindcasted for 35 years, from 1980-2014, with a nearshore fine
631 resolution model that used nested domains. Previous studies, have expressed
632 considerations about the limitations of larger models used in terms of their
633 capabilities to resolve coastal and complex orographic regions. In addition,
634 the selected wind dataset provides with a high temporal input in an attempt
635 to reduce under-estimations, as this is one of the most common problems in
636 wave models.

637 So far, there has not been a long-term fine-resolution coastal wave energy
638 atlas for the region. Our dataset is validated compared with buoy measure-
639 ments, and allowed a detail spatial characterisation of the Greek Seas for
640 wave energy and dominant conditions. The wave climate of the region is ex-
641 amined in terms of the seasonal and annual variation of its parameters with
642 an extensive scope for wave energy sites.

643 Subsequently our resulted dataset is coupled with available published
644 power matrices provided, to deliver for the first time a detail production
645 assessment and performance of WECs for the Greek Seas. Electrical pro-
646 duction estimates show that significant contributions can be achieved by

647 WECs that can benefit the many islands in the Greek Seas. The levels of
648 potential power per device vary according to location as expected, with most
649 favourable WECs operating at low H_s and high frequencies that match the
650 resource characteristics of the Aegean.

651 A preliminary financial sensitivity analysis provides insight for wave en-
652 ergy in the Aegean, for the first time, based on expected production and
653 available schemes promoting RE in Greece. The results show that the uncer-
654 tainty and large range of capital expenditure affects the amortisation peri-
655 ods. Feasible payback periods vary from 7.5 to 13 years, with larger CAPEX
656 leading to not viability under the current assumptions. Although the ini-
657 tial expenditure is high the milder conditions and smaller variability levels
658 provide consistent resource, these conditions can reduce costs and accelerate
659 proof-of-concepts. Acting as a catalyst to assist potential energy contribu-
660 tion by RE to the de-carbonisation of the heavily dependent Greek island
661 system.

662 Based on the results of the study, further analysis can be developed.
663 Firstly, based on disseminated areas a dedicated and even higher resolution
664 assessment can be used to model the wave interactions of WEC farms. The
665 current hindcast dataset can be used for hydrodynamic downscaling analy-
666 sis of "generic" converters. Long-term wave characteristics of high temporal
667 resolution can aid in sizing WEC operation at the region much more effec-
668 tively. Such custom to resource devices will have lower capital and opera-
669 tional expenditures, accelerating the proof-of-concept and providing better
670 economical considerations.

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